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The key kinematic determinants of undulatory underwater swimming at maximal velocity

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1 **TITLE PAGE**

2 **Title:** The key kinematic determinants of undulatory underwater swimming at
3 maximal velocity

4

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27 **Running Title:**

28 Determinants of performance for undulatory underwater swimming
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TITLE PAGE

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Determinants of performance for undulatory underwater swimming

Keywords: maximum velocity, cycle length, cycle frequency, sport science support

ABSTRACT

The optimisation of undulatory underwater swimming is highly important in competitive swimming performance. Nineteen kinematic variables were identified from previous research undertaken to assess undulatory underwater swimming performance. The purpose of the present study was to determine which kinematic variables were key to the production of maximal undulatory underwater swimming velocity. Kinematic data at maximal undulatory underwater swimming velocity were collected from seventeen skilled swimmers. A series of separate backward-elimination analysis of covariance models were produced with cycle-frequency and cycle-length as dependent variables and participant as a fixed-factor; as including cycle-frequency and cycle-length would explain 100% of maximal swimming velocity variance. The covariates identified in the cycle-frequency and cycle-length models were used to form the saturated model for maximal swimming velocity. The final parsimonious model identified three covariates (maximal knee joint angular velocity, maximal ankle angular velocity and knee range of movement) as determinants of the variance in maximal swimming velocity (Adjusted- $r^2=0.929$). However, when participant was removed as a fixed-factor there was large reduction in explained variance (Adjusted $r^2=0.397$) and only maximal knee joint angular velocity continued to contribute significantly, highlighting its importance to the production of maximal swimming velocity. The reduction in explained variance suggests an emphasis on inter-individual differences in undulatory underwater swimming technique and/or anthropometry. Future research should examine the efficacy of other anthropometric, kinematic and coordination variables to better understand the production of maximal swimming velocity and consider the

81 importance of individual undulatory underwater swimming techniques when
82 interpreting the data.

83

84

85 **INTRODUCTION**

86 The optimisation of undulatory underwater swimming, employed during the
87 underwater phase of the starts and turns of three of the four competitive strokes, is
88 vital to ensure the best possible transition from the glide phase into full-stroke
89 swimming (Mason and Cosser, 2000, 2001). According to Mason and Cosser (2000)
90 the production of an effective underwater kicking action is a fundamental factor with
91 respect to the optimisation of swimming performance, as start and turn times are
92 strongly correlated with overall swim time. However, despite this important role in
93 start and turn performance, there is a relative dearth of quantitative research
94 undertaken to specifically identify the key kinematic factors involved in the
95 production of a undulatory underwater swimming action to maximise swimming
96 velocity.

97

98 It has been recognised that undulatory underwater swimming is comparable to an
99 undulatory form of locomotion more commonly associated with aquatic animals
100 (Ungerechts, 1987, 1984, 1982; Sanders *et al.*, 1995; Connaboy *et al.*, 2009).
101 Ungerechts (1984) highlighted that an exceptional feature of swimmers (animal and
102 human) employing an undulatory form of locomotion in an aquatic environment is
103 that the body motions simultaneously provide the propulsive forces and determine

104 the active drag experienced in one unified motion. Greater undulatory underwater
105 swimming velocities are achieved by increasing the magnitude of the propulsive
106 impulse relative to the active drag experienced, and therefore the same maximal
107 swimming velocity can be attained in a number of different ways. For example the
108 same maximal undulatory underwater swimming velocity can be achieved via large
109 undulatory movements which seek to maximise propulsive impulse production with
110 a correspondingly high active drag (high energy requirement/cost), or via smaller
111 movements which produce a reduced amount of propulsive impulse but
112 simultaneously minimise the active drag experienced. A skilled underwater
113 undulatory swimmer would attempt to maximise propulsive impulse by employing
114 optimal amplitudes of the end-effector. In conjunction, the coordinated amplitudes
115 of the preceding sections of the body should be temporally structured in a manner
116 that minimises flow separation (Tokomaru and Dimotakis, 1991; Triantafyllou,
117 2002) and maximises energy reuse from the vortices shed as ‘body wake’ further up
118 the undulating body (Triantafyllou, 1991; Anderson *et al.*, 1998). Unfortunately,
119 these types of kinematic variables are not routinely reported when undertaking
120 biomechanical sports science support for swimmers.

121

122 The positive relationship between cycle frequency of the end-effector (tail or
123 terminal limb segment) has been shown consistently to be a strong predictor of
124 undulatory underwater swimming performance (Bainbridge, 1958; Hunter and
125 Zweifel, 1971; Fish, 1984; Long *et al.*, 1994). However, cycle-frequency alone
126 cannot fully explain all the variations apparent in maximum undulatory underwater

127 swimming between performers. Consequently, the relationship between cycle-
128 frequency and maximal swimming velocity is not simply governed by the selected
129 cycle-frequency, but also by the kinematics used to generate specific cycle-
130 frequency when attempting to maximise undulatory underwater swimming velocity
131 (Taneda, 1978; Tomakaru and Dimotakis, 1991; Anderson *et al.*, 1998). While the
132 relationship between cycle-frequency, cycle-length and movement velocity is well
133 documented and empirically verified for a variety of forms (rowing, kayaking,
134 running, etc.) of locomotion as $\text{Velocity} = \text{Cycle-frequency} \times \text{Cycle-length}$ (Craig &
135 Pendergrast, 1979), this does not provide sufficient information to identify and
136 understand the relative importance of other kinematic variables commonly measured
137 in the execution and analysis of undulatory underwater swimming performance.

138

139 When attempting to analyse swimmers' performance in an applied sports science
140 support setting, the equipment most often available (Waterproof video recorder and
141 simple video analysis software) does not generally allow for detailed analysis of the
142 more complex attributes of undulatory underwater swimming. Therefore, the
143 relevance of variables which are relatively easy to determine and utilised within a
144 sports science support setting requires further investigation. The variables most
145 commonly utilised when describing and/or analysing undulatory underwater
146 swimming include: joint centre (vertical linear displacement) amplitudes (Connaboy
147 *et al.*, 2007a, 2007b; Loebbecke *et al.*, 2009a; Loebbecke *et al.*, 2009b; Connaboy *et al.*,
148 2010; Elipot *et al.*, 2010; Cohen *et al.*, 2012) joint angles, ranges of motion and
149 angular velocities (Arellano *et al.*, 2002; Connaboy *et al.*, 2010; Elipot, *et al.*, 2010),

150 and the angle of attack of the end effector (Elipot, *et al.*, 2010; Connaboy *et al.*,
151 2010). Despite the increase in the number of research studies examining undulatory
152 underwater swimming performance, there is still a paucity of understanding as to
153 exactly which variables are most strongly related to maximal undulatory underwater
154 swimming swimming velocity. Some previous research (Rejman and Borowska,
155 2008) was undertaken to analyse similar, simple kinematic variables and their
156 relationship to overall undulatory underwater swimming performance. However, this
157 form of undulatory underwater swimming included the use of a monofin. Therefore,
158 further research was still required to understand the relative importance of each of
159 these more easily determined kinematic variables with respect to the production of
160 maximal swimming velocity in the undulatory underwater swimming performed in
161 the competitive swimming strokes.

162

163 The purpose of this study was to identify key kinematic determinants of
164 performance for maximal undulatory underwater swimming in skilled swimmers
165 from those routinely analysed when providing sport science support for swimmers.
166 This was accomplished by examining which kinematic variables provided the best
167 predictive models for (a) Cycle-frequency (b) Cycle-length, and subsequently (c)
168 Maximal swimming velocity.

169

170 **METHODS**

171 **Participants**

172 A group of seventeen (eight male and nine female) national level competitive
173 swimmers (Males: Mean \pm SD: age 17.6 \pm 1.4 years, height 177.6 \pm 5.3cm, mass
174 72.7 \pm 7.9kg; Females: age 16.35 \pm 0.8 years, height 164.9 \pm 4.1cm, mass 53.8 \pm 3.0kg)
175 from the ‘*Elite*’ squad of a local swimming club participated in this study. All
176 participants had a minimum of five years of competitive swimming experience
177 (mean 6.9 \pm 1.9 years) and had competed in a national age-group championship final.
178 Ethical approval for the study was granted from the local Ethics Committee.
179 Informed consent was obtained from each participant and if a minor (age below 18
180 years), also from their legal guardian.

181

182 **Experimental protocol**

183 Seven days prior to data collection, participants performed eight trials of the
184 maximal swimming velocity experimental protocol to familiarise themselves with
185 the requirements of the protocol (Connaboy *et al.*, 2010). The experimental protocol
186 consisted of each swimmer performing three maximum effort undulatory underwater
187 swimming trials, with the swimmer in the prone position and the hands and arms
188 held out in front, consistent with the techniques performed in the starts and turns of
189 the freestyle swimming stroke. A total of six cycles of undulatory underwater
190 swimming data (2 cycles per trial) were captured, to ensure that the kinematic data
191 would provide a representative and reliable account of the undulatory underwater
192 swimming kinematics (Connaboy *et al.*, 2010). Prior to undertaking the three trials
193 a standardised (20 minute) warm-up was conducted (Connaboy *et al.*, 2010).

194

Figure 1 About here

196

197 Each trial consisted of the swimmer starting from point A (Figure 1) at the left end
198 of the pool, pushing off the wall and swimming underwater using undulatory
199 underwater swimming. The participants attempted to swim as fast as they could,
200 maximising swimming velocity as they swam through the video recording area. The
201 distance from the wall to the start of the recording zone (10m) was sufficient to
202 ensure that the push off velocity from the wall had no effect on the maximal velocity
203 attained whilst swimming through the testing area (Arellano *et al.*, 2002). In
204 addition, the participants were instructed to only use the push off from the wall to
205 enable them to achieve the correct orientation and depth rather than as a means to
206 maximise velocity. This was done to ensure that any changes in the performance of
207 the push-off did not have an effect on the undulatory underwater swimming
208 performance through the capture area. A depth of between 0.8 and 1.2m below the
209 surface of the water was required to exclude the effects of wave drag (Vennel *et al.*,
210 2006). If participants did not swim between these depths, the trial was rejected and
211 then repeated.

212

213 The participants were instructed to accelerate over the first 10m to attain maximum
214 swimming velocity prior to entering the beginning of the recording area, and to
215 maintain that velocity throughout the entire recording zone (Figure 1). No
216 instructions were given regarding the cycle-frequency employed. A minimum five-
217 minute rest interval between trials was employed to allow a full recovery (Connaboy

218 *et al.*, 2010). Previous research (Connaboy *et al.*, 2010) has shown that the
219 previously stated protocol provides reliable results and demonstrates no systematic
220 bias as a consequence of either fatigue and/or learning effect.

221

222 **Data collection and processing**

223 Participants were marked on the skin surface directly over the joint centres of the
224 wrist, shoulder, hip, knee, ankle and 5th metatarsal phalangeal joint of the foot on the
225 right side of the body with a 3cm diameter circle of black oil-based body paint. The
226 length of each participant's thigh was measured from the greater trochanter to the
227 lateral epicondyle (on land) and was subsequently used as the scale factor (Clothier
228 *et al.*, 2004). Data from Clothier *et al.* (2004) regarding the efficacy of this method
229 reported mean error in segments lengths of 1mm, when segment lengths are derived
230 from the video data. The average length of the thigh segment in pixels (per USS
231 cycle) was calibrated against this subject defined scale factor for each of the
232 respective cycles of undulatory underwater swimming video data (Sanders *et al.*,
233 2009; Connaboy *et al.*, 2010), acting to minimize errors associated with
234 extrapolation error, as the participants swam through the data capture area.
235 Horizontal and vertical pixel ratios of the video data were calculated so that the
236 subject derived scale factor could scaled appropriately in both horizontal and vertical
237 planes.

238

239 A two-dimensional videographic technique was employed to collect position-time
240 data. The participants were video recorded with a stationary underwater camera

241 (KY32 CCD; JVC Corporation, Yokohama, Japan) sampling at fifty fields per
242 second (50Hz), and with a shutter speed of 1/120 s. Every field was digitized giving
243 an effective digitizing rate of 50 Hz. The camera was positioned 12m from the plane
244 of motion of the swimmer with its optical axis perpendicular to that plane and
245 (Figure 1) 1m below the surface of the water. The field of view was 4m in the
246 swimming direction enabling two complete kick cycles to be captured for analysis
247 for each trial.

248

249 A kick cycle comprised a complete upward movement (upbeat) and downward
250 (downbeat) movement identified from the video data as commencing at the frame
251 corresponding to the initiation of an upward movement of the 5th metatarsal
252 phalangeal joint to the frame corresponding to the initiation of the next upward
253 movement. Fifteen additional frames either side of the observed start and end of the
254 two kick cycles were digitised to enable the accurate identification of the start/end
255 points of each cycle and to provide additional data points to minimise errors near the
256 end of the data set due to the data smoothing process (Vint and Hinrichs, 1996). The
257 segment endpoint data were digitised using an Ariel Performance Analysis System
258 (APAS-2000 Ariel Dynamics, 2000, San Diego, CA).

259

260 The raw screen coordinate data output were extracted from the APAS system using a
261 specifically designed Visual Basic (Visual Basic 4.0) programme. This enabled the
262 pixel to real world vertical and horizontal ratios to be determined and scale factors
263 adjusted accordingly. These data were then transformed to produce the raw

264 displacement data, using a participant derived two-dimensional linear scale (Clothier
265 *et al.*, 2004). Each individual frame of the collected video data were calibrated with
266 respect to a scale factor determined from a reference structure of known dimension
267 (thigh length) present within each frame of the video data.

268

269 To minimise distortion of the data as a consequence of the swimmers swimming
270 ‘out of plane’, the axis of the camera remained perpendicular to the required
271 movement of the swimmer, and any swimming trial which deviated from the
272 required line of swimming was not included in the subsequent analysis. For the
273 purpose of this analysis bilateral symmetry was assumed (Connaboy *et al.*, 2010)
274 and only the side of the body facing the camera (right hand side) was digitised to
275 define a five segment model of the swimmer’s body, comprising the arm, trunk,
276 thigh, shank and foot. The digitised coordinates of the raw two-dimensional
277 segment endpoint data were filtered using a Fourier transform. A cut-off frequency
278 for filtering the data was selected at 7Hz, as more than 98% of the power in the
279 displacement-time signals was contained within the harmonics up to 7Hz.

280

281 **Data analysis**

282 The displacement data were input to a specifically designed MATLAB (Mathworks,
283 Inc) programme. The programme calculated the first two derivatives (velocity and
284 acceleration) of the displacement data for the wrist, shoulder, hip, knee, ankle and
285 5th metatarsal phalangeal joint by differentiation using central difference formulae.
286 The start/end points of each kick cycle were then identified based on the four local

287 minima of the y-axis coordinates of the 5th metatarsal phalangeal joint position data.
288 These points represent the minimum vertical displacement values of the foot
289 throughout the two cycles.

290

291 Using the methods employed by Connaboy *et al.* (2010) a total of nineteen
292 kinematic variables already identified as important in undulatory underwater
293 swimming were calculated for each kick cycle: (1) maximal swimming velocity, (2)
294 cycle-frequency, (3) cycle-length; joint ranges of movement of (4) shoulder, (5) hip,
295 (6) knee, (7) ankle; maximum angular velocities of (8) shoulder, (9) hip, (10) knee,
296 (11) ankle; vertical joint centre amplitudes of (12) wrist, (13) shoulder, (14) hip, (15)
297 knee, (16) ankle, (17) 5th metatarsal phalangeal joint; (18) maximum angle of attack
298 of the end-effector, and (19) the mean absolute angle of attack of the end-effector.

299

300 **Statistical Analysis**

301 All statistical analyses were performed using SPSS (PASW Statistics 18.0, SPSS
302 Inc., Chicago, IL). The normality of the data distribution for each dependent variable
303 (DV) was determined using the Kolmogorov-Smirnov test. Backward elimination
304 (BE) ANCOVA models were utilised to ascertain which individual kinematic
305 variable(s) provided the best predictive models for each of the three DVs for all
306 participants (Draper and Smith, 1998). The BE ANCOVA analysis model was
307 selected because it has the capacity to fit a fixed between-subject indicator variable
308 (n=17) and enables the estimation of a within-subject source of variation (6 cycles)
309 as part of the error structure (Nevill *et al.*, 2011; Brown *et al.*, 2011). This enables

310 the ANCOVA analysis to partition the two sources of variation (between and within-
311 subject variation). Participant number was used as a fixed factor to ensure the
312 analysis allowed for individual differences in the respective DVs. With no
313 statistically significant differences ($p < 0.05$) between the sexes for either maximal
314 swimming velocity, cycle-frequency or cycle-length, and to improve the statistical
315 power of the tests performed, the data from both female and male participants were
316 analysed together.

317

318 Through a process of backward elimination a parsimonious or a final (depending on
319 the number of variables retained) model of the determinants of each of the respective
320 DVs was produced. The final model was achieved by a process of iteration, starting
321 with the saturated model containing all the covariates, the least important covariate
322 (as denoted by the largest p -value) was withdrawn from the model and the
323 ANCOVA statistic recalculated. This process was repeated until all the remaining
324 ‘predictor’ variables provided a significant contribution ($p < 0.05$) to the final model
325 (Bridgewater and Sharpe, 1998; Nevill *et al.*, 2010; Nevill *et al.*, 2011). Effect size
326 statistics were determined for each variable contained within the final models using
327 partial-Eta² (η_p^2) (Brown *et al.*, 2011; Cohen, 1988).

328

329 Given the relationship between maximal swimming velocity, cycle-frequency and
330 cycle-length (maximal swimming velocity = cycle-frequency x cycle-length) and
331 that the inclusion of cycle-frequency and cycle-length into a statistical model
332 designed to determine the relationship between kinematic variables and the

333 production of maximal swimming velocity would explain the entire variance in
334 maximal swimming velocity ($r^2=1.00$), separate BE ANCOVA models were used to
335 determine which of the kinematic variables were best able to explain the variation
336 for each of cycle-frequency and cycle-length from all the 102 data cycles (17
337 participants \times 3 trials \times 2 cycles). Both cycle-frequency and cycle-length were
338 excluded from the final model (DV= maximal swimming velocity) and the results
339 from the initial series of ANCOVA models for cycle-frequency and cycle-length,
340 were used to determine which variables would be entered into the initial ‘saturated’
341 ANCOVA model to analyse maximal swimming velocity.

342

343 **RESULTS**

344 The kinematic data for all the swimmers were determined (Table 1). The data from
345 all participants’ six trials were analysed in the BE ANCOVA.

346

347 ***** Table 1 about here *****

348

349 **Analysis of covariance: Backward elimination models**

350 After the alternate removal of the respective DV’s, the remaining kinematic
351 variables were entered as covariates in separate, saturated ANCOVA models for
352 kinematic variables to determine the best predictive models for cycle-frequency and
353 cycle-length. Through an iterative backward elimination process the separate
354 saturated ANCOVA models were reduced to parsimonious/final models containing

355 only those covariates which significantly ($p < 0.05$) explained a portion of the
356 variance of the DV (cycle-frequency or cycle-length) (Table 2).

357

358 **End-effector cycle frequency**

359 Through the iterative process, the initial saturated model containing all the
360 covariates was reduced to a final model containing only seven covariates (Table 2)
361 which all contributed to an explanation of the variance of cycle-frequency: shoulder
362 amplitude ($p < 0.001$; $\eta_p^2 = 0.149$), ankle amplitude ($p < 0.001$; $\eta_p^2 = 0.472$), max hip
363 angular velocity ($p < 0.001$; $\eta_p^2 = 0.184$), max knee angular velocity ($p < 0.001$; $\eta_p^2 =$
364 0.366), max ankle angular velocity ($p < 0.001$; $\eta_p^2 = 0.317$), knee range of movement
365 ($p < 0.001$; $\eta_p^2 = 0.261$), mean absolute angle of attack ($p < 0.001$; $\eta_p^2 = 0.183$). The
366 fixed factor (Participant) significantly contributed to the model ($p < 0.001$; $\eta_p^2 =$
367 0.670). The adjusted r^2 value was 0.942 .

368

369 **Cycle length**

370 For cycle-length the final model for the kinematic variables was reduced to six
371 covariates: wrist amplitude ($p < 0.01$; $\eta_p^2 = 0.126$), ankle amplitude ($p < 0.001$; $\eta_p^2 =$
372 0.508), max hip angular velocity ($p < 0.001$; $\eta_p^2 = 0.151$), max ankle angular velocity
373 ($p = 0.01$; $\eta_p^2 = 0.088$), shoulder range of movement ($p < 0.05$; $\eta_p^2 = 0.063$), mean
374 absolute angle of attack ($p < 0.001$; $\eta_p^2 = 0.229$). The fixed factor (Participant)
375 significantly contributed to the model ($p < 0.001$; $\eta_p^2 = 0.852$). The adjusted r^2 was
376 0.941 .

377

378 ***** Table 2 about here *****

379

380 **Final Model - Maximal undulatory underwater swimming velocity**

381 The two initial BE ANCOVA models for cycle-frequency and cycle-length
382 identified a total of nine covariates as determinants of the variance of these DVs.

383 The BE ANCOVA models conducted to analyse the kinematic variables in relation
384 to cycle-frequency and cycle-length contained seven and six covariates in their
385 respective final models, with four covariates common to both models (ankle
386 amplitude, max hip angular velocity, max ankle angular velocity and mean absolute
387 angle of attack). The explained variance for each of the respective final models was
388 large (cycle-frequency adjusted $r^2=0.942$; cycle-length adjusted $r^2=0.941$). All the
389 variables included in the final cycle-frequency final model achieved a large effect-
390 size statistic (as denoted by $\eta_p^2>0.1379$; Cohen, 1988; Richardson, 2011). However,
391 for the cycle-length final model, only ankle amplitude, max hip angular velocity and
392 mean absolute angle of attack achieved a large η_p^2 ; with wrist amplitude, max ankle
393 angular velocity and shoulder range of movement achieving a medium effect size
394 ($\eta_p^2>0.0588$).

395

396 The covariates identified from the resultant final models from the cycle-frequency
397 and cycle-length backward elimination ANCOVA's, formed the initial saturated
398 model to examine maximal swimming velocity. The initial model contained all nine
399 of the covariates (wrist amplitude, shoulder amplitude, ankle amplitude, max hip
400 angular velocity, max knee angular velocity, max ankle angular velocity, Shoulder

401 range of movement, knee range of movement and mean absolute angle of attack)
402 identified in the previous BE ANCOVA models.

403

404 The final parsimonious model for maximal swimming velocity revealed max knee
405 angular velocity ($p < 0.001$; $\eta_p^2 = 0.253$), max ankle angular velocity ($p < 0.01$; $\eta_p^2 =$
406 0.115) and knee range of movement ($p < 0.01$; $\eta_p^2 = 0.103$) to account for a large
407 amount of the variance in maximal swimming velocity with adjusted $r^2 = 0.939$. The
408 fixed factor (Participant) significantly contributed to the model ($p < 0.001$; $\eta_p^2 =$
409 0.915). When the fixed factor (Participant) was removed from the model and the
410 ANCOVA re-run, the explained variance reduced (adjusted $r^2 = 0.397$) (see Table 2).
411 In addition, when the fixed factor (Participant) was removed from the model, max
412 ankle angular velocity ($p = 0.779$; $\eta_p^2 = 0.001$) and knee range of movement
413 ($p = 0.361$; $\eta_p^2 = 0.009$) no longer provided a statistically significant contribution to
414 the model, leaving only max knee angular velocity ($p < 0.001$; $\eta_p^2 = 0.395$).

415

416 **Discussion**

417 The purpose of this study was to identify key kinematic determinants of
418 performance for maximal undulatory underwater swimming in skilled swimmers
419 from those routinely analysed when providing sport science support for swimmers.
420 This was accomplished by examining which kinematic variables provided the best
421 predictive models for (a) cycle-frequency (b) cycle-length, and ultimately (c)
422 maximal swimming velocity. Some of the data from the nineteen kinematic
423 variables analysed within the present study of skilled swimmers (Table 1) were

comparable to data reported in previous research. The maximal swimming velocity values reported (mean maximal swimming velocity = $1.20 \pm 0.13 \text{ m.s}^{-1}$) within the present study are similar to those reported for the male and female, national standard age-group swimmers (mean maximal swimming velocity = 1.15 m.s^{-1}) by Arellano *et al.* (2002), but lower than those reported by Loebbecke *et al.* (2009a) and Arellano *et al.* (2002) for Olympic level (mean maximal swimming velocity = 1.45 m.s^{-1}) and international level (mean maximal swimming velocity = 1.61 m.s^{-1}) swimmers, respectively. The cycle-frequency values found within the current study (mean cycle-frequency = $2.13 \pm 0.23 \text{ Hz}$) are very similar to the international swimmers (mean CF = 2.14 Hz), but higher than those reported for national age-group swimmers (mean cycle-frequency = 1.76 Hz) (Arellano *et al.* 2002). The cycle-frequency values from the current study also closely match the cycle-frequency of the male collegiate swimmers (cycle-frequency = 2.11 Hz) from Connaboy *et al.* (2007a) and the male and female Olympic level swimmers (cycle-frequency = 2.18 Hz) analysed by Loebbecke *et al.*, (2009a). The cycle-length data for the skilled age-group swimmers from the present study (mean cycle-length = $0.57 \pm 0.17 \text{ m}$) are lower than both the international (mean cycle-length = 0.76 m) and national level (mean cycle-length = 0.67 m) swimmers cycle-length data reported by Arellano *et al.* (2002), and the mean cycle-length (0.67 m) derived from the mean maximal swimming velocity and cycle-frequency data reported for Olympic level swimmers (Loebbecke *et al.*, 2009a).

446 The similarities in cycle-frequency and the differences in cycle-length and the
447 maximal swimming velocity apparent between the skilled age group swimmers
448 from the current study and the Olympic/International level swimmers, highlights the
449 competing factors which determine the maximal swimming velocity and the manner
450 by which it can be achieved; namely (i) the requirement to simultaneously produce a
451 propulsive impulse and minimise active drag with the same movements (Ungerechts,
452 1984), and (ii) the different kinematics employed to produce them. The skilled
453 swimmers within the present study were able to attain similar cycle-frequency
454 values, and attain similar or higher amplitudes for the end effector (0.61m)
455 compared to the international (0.62m) and Olympic (0.53m) swimmers analysed by
456 Arellano *et al.* (2002) and Loebbecke *et al.* (2009a), respectively. However, the
457 kinematics which brought about these similarities in cycle-frequency and end
458 effector amplitude ultimately led to a comparatively lower cycle-length, and
459 ultimately lower maximal swimming velocity.

460

461 The final parsimonious model for maximal swimming velocity demonstrated that
462 three covariates (maximum knee angular velocity, maximum ankle angular velocity
463 and knee range of movement) accounted for a large amount of the variance in
464 maximal swimming velocity (adjusted $r^2=0.929$). When the fixed factor (Participant)
465 was removed from the model and the ANCOVA re-run, the explained variance
466 reduced (adjusted $r^2=0.397$) and only maximum knee angular velocity provided a
467 statistically significant contribution to the model (Table 2). The reduction of the
468 predictive quality of the model from 92.9% down to 39.7% of the explained variance

469 in maximal swimming velocity demonstrates that the individual manner in which the
470 age-group swimmers are achieving maximal swimming velocity may be largely
471 dependent on the participant's own undulatory underwater swimming technique
472 employed and that the individual undulatory underwater swimming technique is an
473 important predictor of maximal swimming velocity. This interpretation of the BE
474 ANCOVA data suggests that the reduction in explained variance with the removal of
475 participant as a fixed-factor may be representative of the number of possible
476 solutions to the task (maximise undulatory underwater swimming velocity) in
477 relation to the individual's own organismic constraints (e.g. limb segment lengths)
478 (Newell, 1986). Therefore, the skilled age-group swimmers may be exploiting their
479 own, idiosyncratic organismic constraints to maximise propulsive impulse while
480 simultaneously minimising active drag, in response to those constraints imposed by
481 the task and the environment (Newell, 1986). This can be exemplified from the data
482 of two swimmers with identical mean maximal swimming velocity values ($1.18\text{m}\cdot\text{s}^{-1}$).
483 For example, swimmer A has the lowest amplitude of the end effector (5th
484 metatarsal phalangeal joint) of the entire group (0.52 m) while swimmer B has the
485 2nd highest (0.69 m). In addition, swimmer A also has the second highest end-
486 effector cycle-frequency (2.22 Hz) reported within the group, while swimmer B has
487 the 3rd lowest cycle-frequency (1.98 Hz). However, the cycle-length for both
488 swimmers (Swimmer A = 0.53 m, Swimmer B = 0.59 m) is relatively close to the
489 mean value reported for the group (Group mean cycle-length = 0.57 m). These
490 differences in 5th metatarsal phalangeal joint amplitude and cycle-frequency could
491 suggest different movement solutions to the task of maximising undulatory

492 underwater swimming velocity, possibly as a consequence of differences in
493 organismic constraints such as: force production capabilities at specific joints,
494 differences in relative limb/body segment lengths, etc.

495

496 The final parsimonious model for maximal swimming velocity show three
497 covariates providing statistically significant contributions, with either a large effect
498 size (maximal knee angular velocity) or medium/small effect sizes (maximum ankle
499 angular velocity and knee range of movement) depending on whether participant
500 was included as a fixed factor (Table 2). Of the respective individual relationships
501 between the three identified variables and maximal swimming velocity , only
502 maximum knee angular velocity revealed a substantial positive correlation ($r=0.63$)
503 with maximal swimming velocity showing that as the maximum knee angular
504 velocity increased maximal swimming velocity also increased. While both
505 maximum ankle angular velocity and knee range of movement while provided a
506 significant contribution to the final ANCOVA model the individual relationships
507 between them and maximal swimming velocity were 0.08 and 0.15, respectively.
508 Following the removal of 'subject' as a fixed factor from the model, only maximal
509 knee angular velocity provided a significant explained variance in maximal
510 swimming velocity, suggesting that maximal knee angular velocity is the primary
511 variable of interest.

512

513 However, the reduction in explained variance seen when participant as a fixed factor
514 was removed from the model could also be indicative of the exclusion of important

515 variables (covariates) which were not analysed within the present study. Future
516 research should examine the efficacy of other kinematic, coordination and/or
517 anthropometric variables to better understand the interacting effects of the imposed
518 constraints (organismic, environmental and task) on the production of maximal
519 swimming velocity. Factors such as inter and intra-limb coordination and their
520 respective contributions to the simultaneous production of the propulsive and active
521 drag forces should be considered. Furthermore, subject-specific analyses (i.e. single
522 subject analyses, Stergiou, 2004) need to be employed to consider the importance of
523 individual undulatory underwater swimming techniques when interpreting the data.

524

525 Caution should also be taken when interpreting the results as important limitations
526 should be recognised. For example, the mean angle of attack data from the present
527 study were higher than the 15°-25° range suggested for optimal thrust production
528 (Sfakiotakis *et al.*, 1999; Videler and Kamermans, 1985; Triantafyllou *et al.*, 1993).
529 However, the representation of angle of attack as a discrete variable (mean absolute
530 angle of attack) does not fully explain its behaviour and relevance to undulatory
531 underwater swimming performance. It is understood that the maintenance of a
532 positive angle of attack enables thrust to be produced throughout a larger proportion
533 of the stroke cycle (Fish and Rohr, 1999; Lighthill, 1969; Videler and Kamermans,
534 1985). The mean value for angle of attack does not allow an examination of the
535 proportion of the time spent with a positive value for angle of attack or the time
536 within the theoretically optimal range. Therefore, future analyses should look to
537 incorporate either a greater number of discrete measures of data at key points in the

538 movement cycle, or combine both discrete and continuous measures of variables
539 such as angle of attack to provide a detailed examination of their relevance to the
540 production of maximal swimming velocity in skilled swimmers.

541

542 In conclusion, three covariates: max knee angular velocity, max ankle angular
543 velocity and knee range of movement were found to explain a significant proportion
544 of the variance in maximal swimming velocity (92.9%). However, the large
545 reduction (53.2%) in explained variance following the removal of participant as a
546 fixed-factor suggested that individual swimmers were employing different
547 techniques when attempting to maximise undulatory underwater swimming velocity.
548 However, consistent among all participants was the identified relationship between
549 maximal knee angular velocity and maximal swimming velocity; emphasising
550 importance of a fast knee extension in the production of maximal undulatory
551 underwater swimming performance.

552

553 Alternatively, other important variables not currently analysed, were missing from
554 the predictive model, suggesting that the kinematic variables analysed are
555 insufficient for providing a comprehensive assessment of USS performance.
556 Therefore, further analysis is required to establish which constraints are influencing
557 the kinematics employed by skilled undulatory underwater swimmers when
558 attempting to maximise undulatory underwater swimming velocity, incorporating a
559 more comprehensive list of relevant variables. Once a more complete model has be
560 examined and the key determinants of undulatory underwater swimming

561 established, further recommendations can then be made as to which kinematic
562 variables sports scientists should analyse when supporting skilled swimmers.

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